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FLOW CALORIMETERS FOR THE 4-MM AND 2-MM WAVELENGTH RANGE

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FOREWORD

The author wishes to express his appreciation to Mr. Donald J. Nicholson for the many helpful suggestions made during this investigation.

Acknowledgement is also made to Dr. G. Heller, Mr. G. Catuna, and Mr. B. Thaxter of Lincoln Laboratory for their helpful discussions during the preliminary stages of the calorimeter design.

ABSTRACT

Present commercial calorimeters operating at wavelengths below four millimeters are limited to the measurement of a maximum of one-half watt of average power, thus requiring the use of precision calibrated attenuators for higher powers. This report describes the mechanical and electrical characteristics of a 4-millimeter (50 to 75 kmc/s) and a 2-millimeter (90 to 140 kmc/s) flow calorimeter capable of measuring several watts of average power. These calorimeters have an advantage over commercially available units by being capable of direct power measurements from one milliwatt to several watts without the use of auxiliary components.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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INTRODUCTION

One of the parameters that defines the characteristics of a microwave or millimeter wave source is the power output. Various devices have been developed to measure the power output of sources such as magnetrons, klystrons, backward wave oscillators, and carcinotrons. These devices include bolometers, thermistors, and calorimeters. Bolometers and thermistors are limited in their range of direct power measurement to approximately 50 milliwatts. Above this power level the small volume of the element cannot dissipate the power absorbed, and the device overheats and fails. Thus, attenuators are required to reduce the power to a safe level. In calorimetric devices, power is dissipated in a load and the temperature rise of the load, or of a cooling fluid flowing in or around the load, is measured and then calibrated in terms of power. The maximum power-handling capacity of these devices is limited only by the thermal capacity of the load.

In the dry or static calorimeter type, the temperature rise of an active microwave load is compared to a dummy load maintained at ambient temperature. By supplying d-c power to the active load, consisting of a known resistance, a calibration of d-c power versus thermopile voltage may be obtained.

Flow-type calorimeters have advantages over the fixed thermistor or bolometer elements because of their dynamic power range. By adjustment of the flow rate, direct power measurements in the range of one milliwatt to several watts are feasible. The liquid calorimeter[1] utilizes a thermopile located in the input and output flow tubes connected to the microwave load. When microwave power is incident on the water load, a temperature rise occurs in the liquid and produces a temperature difference between the hot and cold junctions of the thermopile.

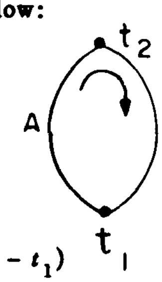
For greatest accuracy of measurement, the fluid flow rates of the flow calorimeter should be adjustable. The temperature rise of the liquid should not exceed the capability of the thermopile employed; that is, the drift rate should be much less than the thermopile output voltage. Large flow rates cause the temperature rise to be small, resulting in errors in the temperature to be measured. Small flow rates lead to erratic performance because of insufficient mixing of the fluid. Turbulence should be maintained in the flow tubes to prevent laminar flow, which may cause temperature gradients to exist over the cross section of the tube. In the case of the millimeter calorimeters utilizing small flow tubes with thermocouples centered in them, a certain amount of mixing should occur, thus minimizing errors due to the laminar flow which exists because of the diameter and flow rate.

In this report, the mechanical and electrical characteristics of a 4-millimeter and a 2-millimeter flow calorimeter are described which are capable of measuring several watts of average power. Distilled water was used for the calorimetric fluid because of its high loss at millimeter wavelengths and its high thermal capacity. Measurement of the loss tangent of water at microwave frequencies indicates high loss characteristics as the frequency is increased toward 30 kmc.[2] Measurements of insertion loss and reflection coefficient from water samples at 4 and 2 millimeters indicated that it was possible to obtain a well-matched load in a minimum length when utilizing the high loss characteristics of water in the load.

RELATIONSHIP OF AVERAGE POWER TO THERMOELECTRIC EMF

Seebeck[3] discovered that a current will flow in a circuit composed of two dissimilar metallic conductors, if a temperature difference exists between the two junctions. The thermoelectric voltage generated will depend upon the material used for the junctions and the thermal conditions present at the junctions. This device is known as a thermocouple and has found many applications in temperature measurements.

Copper-constantan thermocouples were selected for this particular application because of their high thermoelectric power[4] at average room temperatures with a fairly low resistivity and a good resistance to oxidation up to 400° C. The temperature range of interest for this application was in the 20° C. to 30° C. (68° F - 86° F.) range. The thermoelectric emf produced between a hot and cold junction of two dissimilar metals A and B at temperatures of t_2 and t_1 is as shown below:



$$E_{AB} = e(t_2 - t_1)$$

e = emf generated per degree centigrade
t_2 = hot junction temperature ° C.
t_1 = cold junction temperature ° C.

For a 1.0° C. change, e = 40 microvolts for a copper-constantan thermocouple (see Figure 1) and

$$E_{AB} = 40 \text{ microvolts.}$$

Therefore, for any number of junctions, the total emf will be

$$E_{AB} \text{ total} = N[e(t_2 - t_1)]$$

where N = the number of junction pairs.

The average power measured by a circulating or flow calorimeter may be calculated from the following:[5]

For the flow calorimeter

$$P \text{ (watts)} = K' v \, \Delta T$$

where v is velocity in cc/minute

ΔT = temperature change in ° C.

The value of K' depends upon the appropriate constants for H_2O. Thus, one must measure v and ΔT. The velocity (v) is measured directly on a Fisher Flowmeter Kit (Cat. No. 11-164), as will be described, and ΔT is measured by the thermopile and given by:

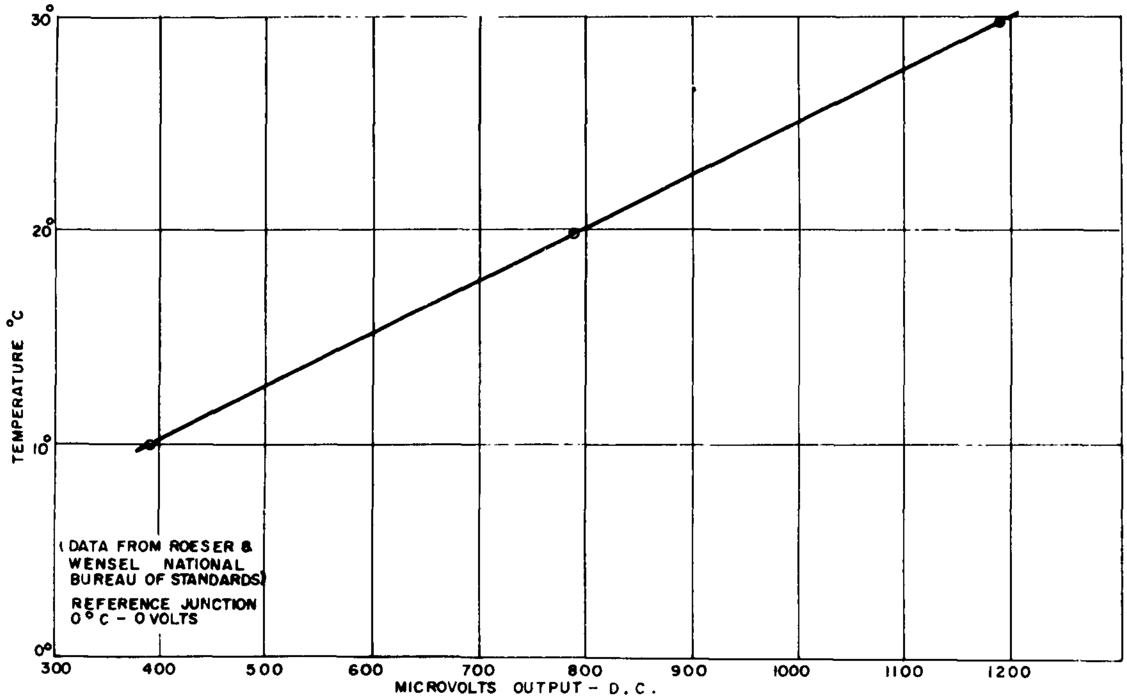


Figure 1. Temperature Versus EMF for Copper-Constantan Thermocouple.

$$\Delta T = \frac{E_{AB}}{N} = \frac{E\ (\mu\text{volts})}{2000}.$$

The final measurement is thus a voltage at a particular water flow rate, and power is given by:

$$P\ (\text{watts}) = \frac{K' v \frac{(cc)}{min} E\ (\mu\text{volts})}{2000}$$

$$K' = (C_p)\,(d)\,(J)$$

where C_p = specific heat of fluid (calories/gram) for H_2 0 1 cal/gr
d = specific gravity of fluid (gram/cm^3), for $H_2$0 1 gr/cm^3
J = 4.187 joules/calories
(mechanical equivalent of heat)

Conversions:

1 calorie/second = 4.187 joules/second

1 watt = 1 joule/second

and K with the appropriate conversion units is:

$$K = \frac{K'}{1.2 \times 10^5}$$

Therefore, $P(w) = \dfrac{4.187}{1.2 \times 10^5}\ v\ \dfrac{(cc)}{min}\ E\ (\mu volts)$

e.g., for a temperature change $T = 1 \times 10^{-3}\ ^\circ C$,

and $v = 1$ cc/min

$$E(\mu volts) = 2.000 \times 1 \times 10^{-3} = 2.0$$

and $P(w) = 3.5 \times 10^{-5} \times 1.0 \times 2.0$

$P(w) = 70.0 \times 10^{-6}$ watts or 70 μwatts

Therefore, if one knows the flow rate precisely and the characteristics of the thermopile*, the power may be calculated as shown above for flow calorimeters.

CONSTRUCTION OF FLOW CALORIMETERS (4 MM - 2 MM)

1. Four-Millimeter Calorimeter

The first 4-mm calorimeter constructed was limited to the measurement of minimum power levels of one milliwatt. It consisted of a 20-junction copper-constantan thermopile producing 0.4 microvolt/$1 \times 10^{-3}\ ^\circ C$. This sensitivity was sufficient for measuring the several hundred milliwatts of power produced by the COE-40, CSF carcinotrons ($f_0 \simeq 70$ kmc/s). A setup of this first calorimeter is shown in Figure 2.

For power measurement at 2 mm, work has started on a more sensitive calorimeter design. At the time of its inception, 2-mm tubes were not available; therefore, the design capabilities were proven at 4 mm after which a 2-mm model was constructed.

In order to achieve greater power sensitivity, the number of thermocouple elements used was increased to one hundred junctions. This construction posed more problems than the original 20-element configuration. Due to the increased sensitivity of the calorimeter, the finite temperature variations caused instability in the output voltage.

The flow tubes and thermopile construction are shown in Figure 3. The tubes (Biraco Type 315C, having a .053" inside diameter) are mounted in a piece of Plexiglas. One-fourth the circumference of these tubes, in the inner plastic well, is exposed for insertion of the thermocouple junctions. The holes for inserting the thermocouples are .020" in diameter and spaced at 0.80" intervals. The thermocouple holes are sealed with B.F. Goodrich Industrial Adhesive A851. The plastic well is then filled with paraffin wax for good thermal isolation. The flow tube in the r-f load section consists of a teflon tubing .053" inside diameter. Teflon tubing was used in the load section, since this material exhibits low loss even at millimetric wavelengths. (See detailed drawings in Appendix II.)

The completed thermocouple and load structure with its associated tubing connections are depicted in Figure 4. Approximately ten turns of 1/8" outside diameter copper tubing are wound around the structure and are intimately in contact with the brass waveguide.** This tubing maintains temperature equilibrium between the water and r-f load walls to eliminate fluctuations in output voltage. The calorimeter structure is enclosed in a copper cylinder filled with an insulating material to minimize external temperature effects. Figure 5 shows the completed 4-mm and 2-mm calorimeters.

* See Appendix I.

** Lincoln Laboratory assistance (Dr. G. Heller, Mr. G. Catuna, and Mr. B. Thaxter).

Figure 2. The 4-MM Calorimeter.

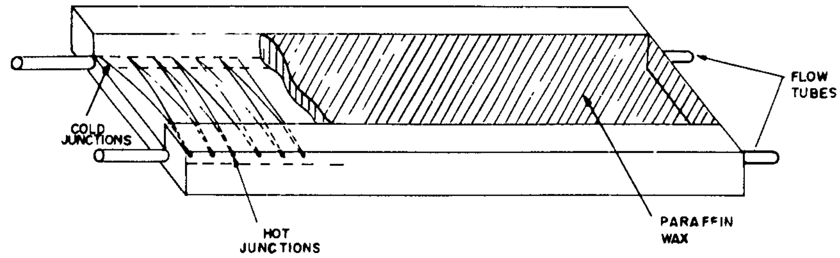


Figure 3. Thermopile Construction, 4-MM Calorimeter.

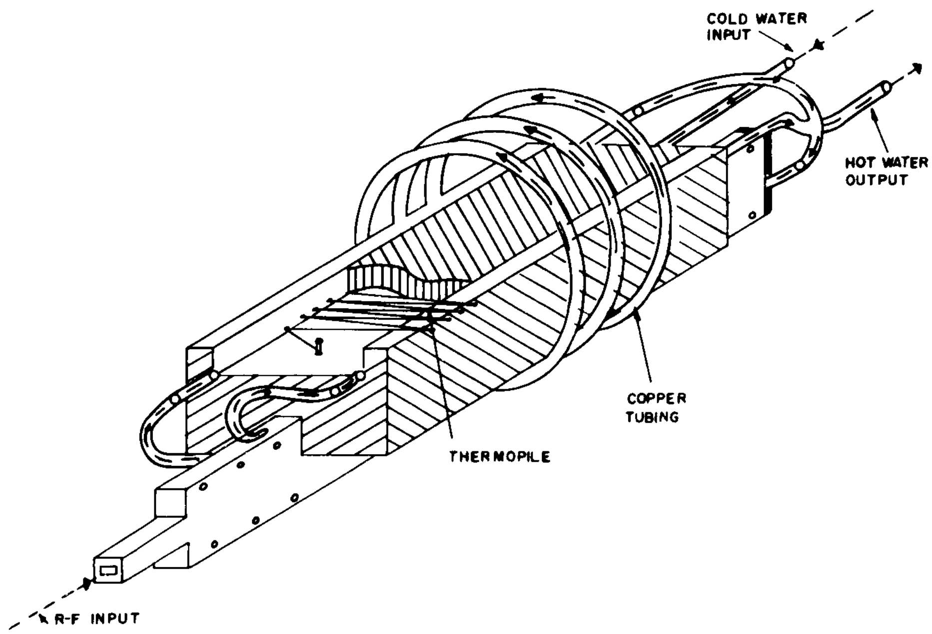


Figure 4. Flow Diagram, 4-MM Calorimeter.

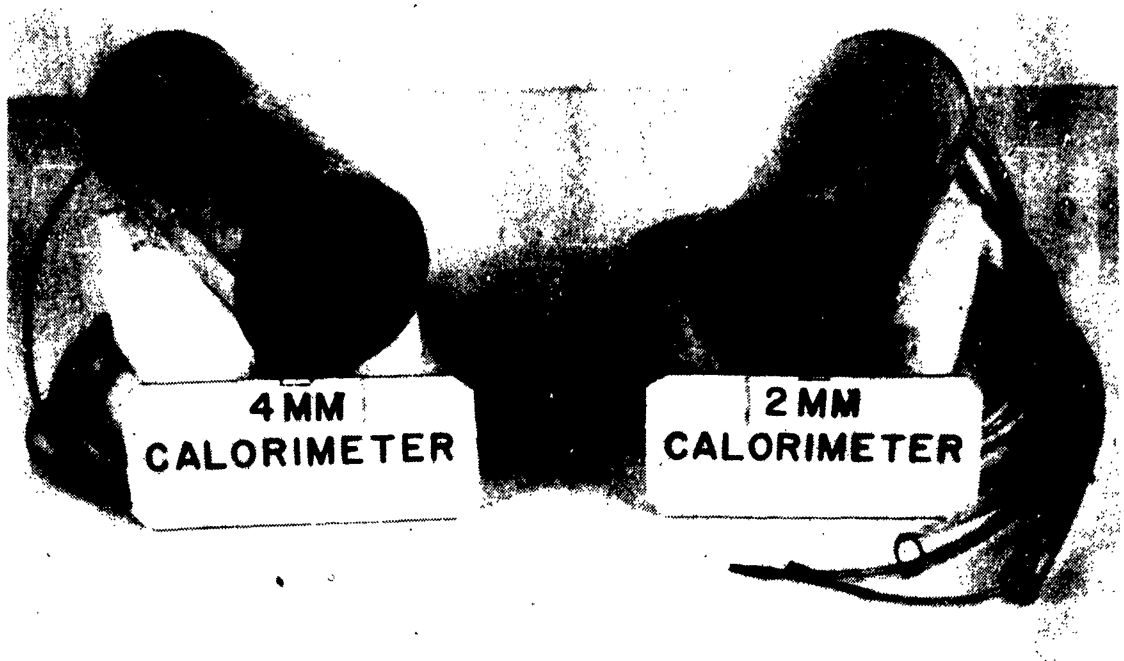


Figure 5. Comparative Views, 4-MM and 2-MM Calorimeters.

2. Two-Millimeter Calorimeter

Several modifications were made in the 2-mm thermopile block assembly due to the development of leaks and instability in the 4-mm model.

The r-f load assembly is similar to the 4-mm model except for waveguide dimensions and a teflon bushing inserted into the top flow tube opening to minimize heat loss.

A Plexiglas split block assembly was used for mounting the thermocouple elements. The hot and cold junction assembly is shown in Figure 6.

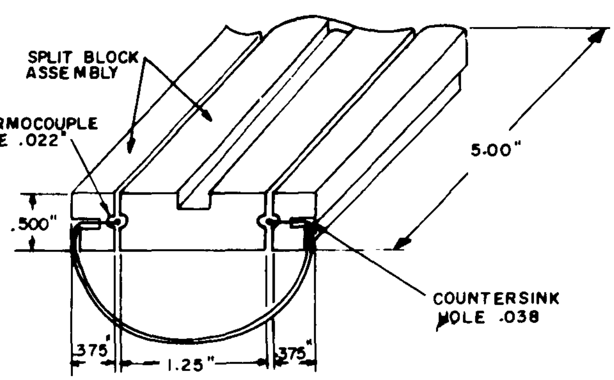


Figure 6. Hot and Cold Junction Assembly, 2-MM Calorimeter.

The thermocouple elements were then sealed using ethyl-dichloride solvent and powdered Plexiglas. Upon completion of the hot and cold junction elements, the split block assembly was bonded using the ethyl-dichloride solvent. This design eliminated the plastic flow tubes used in the previous model of the block assembly. The length of the thermocouples was increased to minimize the conductance of heat between the hot and cold junctions. Figure 7 shows the load and thermopile assembly.

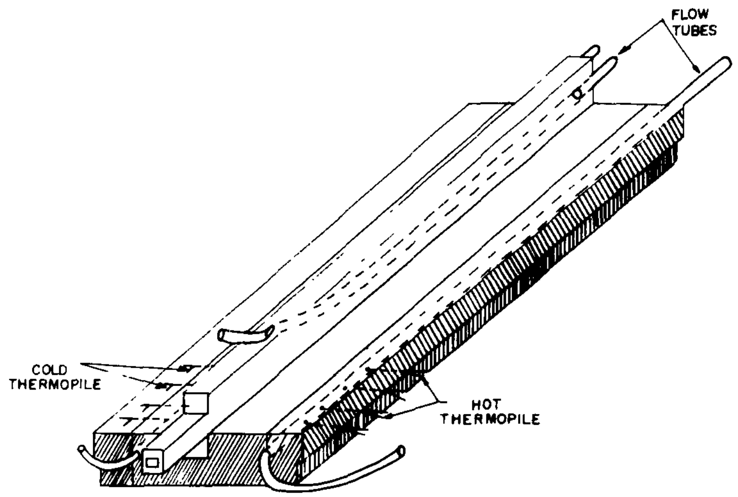


Figure 7. Load to Thermopile, 2-MM Calorimeter.

The connecting flow tubes used in the 2-mm model are the same as in the 4-mm model with the exception of the teflon tube in the r-f load section. It was necessary to reduce the size to .032" inside diameter and a .010" wall thickness due to the smaller waveguide dimensions. The remainder of the construction is similar to the previous model.

D-C CALIBRATION

Provisions are made for calibrating the calorimeters with d-c power. The d-c calibrator consists of a precise length of No. 40 manganin resistance wire (≈ 31.0 ohms/ft) positioned in the portion of teflon tubing exposed to the r-f energy. This positioning of the resistance element produces the same heating effects as the average r-f energy, and thus eliminates errors due to r-f and d-c heating occurring in regions possessing different thermal losses. From a knowledge of the resistance (R) of the heater and the current flow (I), the d-c power can be calculated:

$$P_{DC} = I^2 R$$

Then, from the flow calorimetric equation:

$$P \text{ watts} = K' v \Delta T$$

and

$$P_{DC} = P_{RF} = P \text{ (watts)}$$

where P_{DC} and P_{RF} are the same average power.

It is assumed that the P_{RF} (average power) incident upon the load is completely absorbed and will produce the same heating effects as the P_{DC}, an implicit assumption in all operational definitions of average r-f power.

The d-c efficiency of the flow calorimeters is less than 100 percent, as noted in the d-c calibration curves of Figures 8 and 9. The contributing factors for this deficiency are: (1) loss in the temperature differential (ΔT) of the hot and cold junctions due to thermal conduction of the thermocouple wires; (2) lack of sufficient turbulence; and (3) loss of heat to the surrounding metallic waveguide walls. The d-c efficiency is:

$$\text{D-C efficiency (\%)} = \frac{P_{DC}(\text{measured})}{P_{DC}(\text{calculated})} \times 100\%$$

This d-c efficiency figure gives a correction factor to account for the thermal losses previously mentioned. This factor, coupled with the d-c calibration, provides the standard value for voltage output versus power input, and the r-f power is measured in terms of this standard.

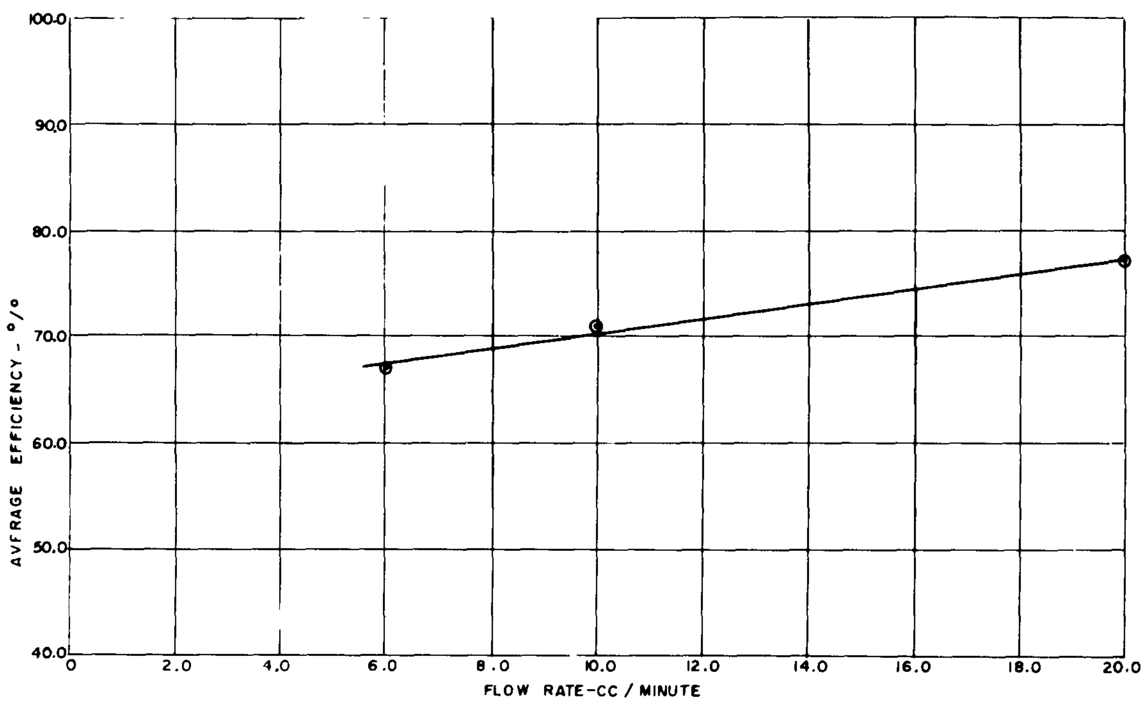


Figure 8. D-C Calibration Curve, 4-MM Calorimeter.

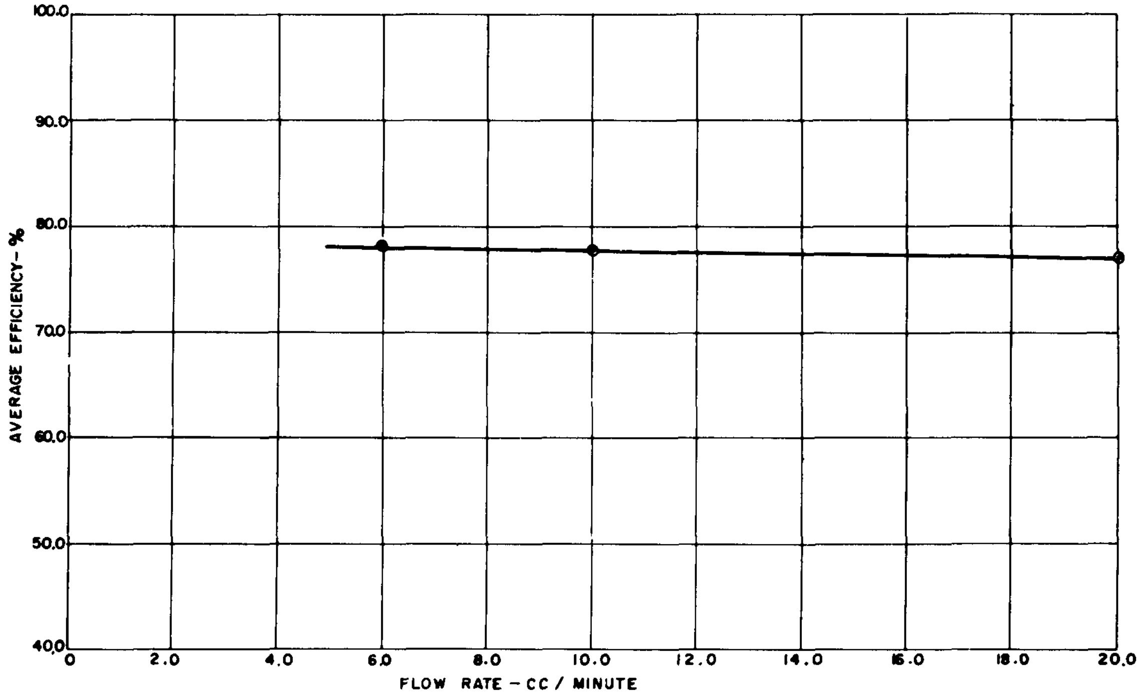


Figure 9. D-C Calibration Curve, 2-MM Calorimeter.

R-F EFFICIENCY

R-F efficiency is defined here as the percentage of incident r-f power that is absorbed by the water load to the total r-f power at the input of the calorimeter.

$$\text{R-F efficiency (\%)} = \frac{P_{RF}\text{(absorbed)}}{P_{RF}\text{ (at input)}} \times 100\%$$

This is, therefore, a measure of how well the microwave circuitry delivers r-f power to the water load.

There are several parameters which determine the overall r-f efficiency of a calorimeter and which must be taken into account for a particular power measurement.

At the millimeter wavelengths, the attenuation of rectangular waveguide becomes appreciable, and a correction factor must be used for precise power measurements. For a 50.0 - 75.0 kmc/s silver waveguide, the attenuation is approximately .5 db/ft at lowest operating frequency and .4 db/ft at the highest operating frequency of the TE_{10} mode. This attenuation corresponds to a loss factor of 11.0 - 9.0% respectively. Therefore, the power loss due to the waveguide load section is of the order of 5%. For a 2-mm waveguide (90 - 140) kmc/s, the loss figure shows a three-fold increase in attenuation. The attenuation for this particular silver waveguide is 1.5 db/ft at the lowest operating frequency and 1.0 db/ft at the highest operating frequency, with a corresponding power loss of 16.0 - 11.0%. Figure 10 is a plot of the attenuation versus frequency for both 4-mm and 2-mm waveguides.

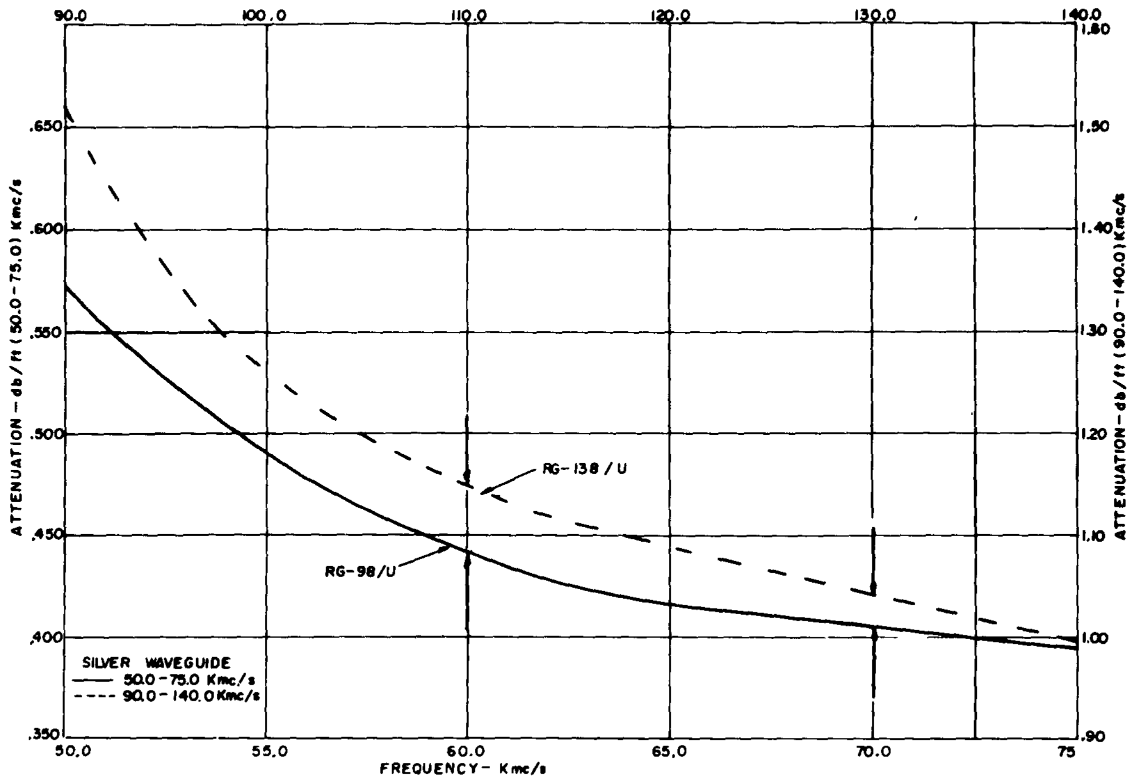


Figure 10. Silver Waveguide Attenuation, 50 - 140 kmc/s.

Another accountable loss factor is the attenuation loss in the flow tubes. Although teflon is one of the better low loss dielectrics at microwave wavelengths the loss tangent increases at the millimeter wavelengths. Our measured values of the teflon tubing loss are given below.

Frequency kmc/s	Tubing Dimensions		Attenuation loss db/10cm
	I.D. (inches)	Wall thickness (inches)	
73.7	.053	.012	.3
136.0	.027	.010	.5

A second important r-f parameter is the waveguide impedance (Z_L) of the load. When Z_L is equal to the characteristic wave impedance of the waveguide (Z_0), there is a perfect match and all the energy incident on the load will be absorbed. When $Z_L \neq Z_0$ there will be energy reflected. This energy is related to the voltage standing wave ratio (VSWR) of the transmission line.

The magnitude of the voltage reflection coefficient $|\Gamma|_v$ is

$$|\Gamma|_v = \frac{\text{VSWR}-1}{\text{VSWR}+1} = \frac{Z_L - Z_0}{Z_L + Z_0}.$$

The magnitude of the power reflection coefficient is

$$|\Gamma|_p = |\Gamma|_v^2.$$

Hence, the amount of power reflected is

$$P_{\text{reflected}} = |\Gamma|_v^2 \times 100\%.$$

Figure 11 is a plot of the percentage of incident power reflected versus VSWR. A VSWR of magnitude greater than 1.20 will cause errors > 1.00% and should be accounted for in a precise measurement.

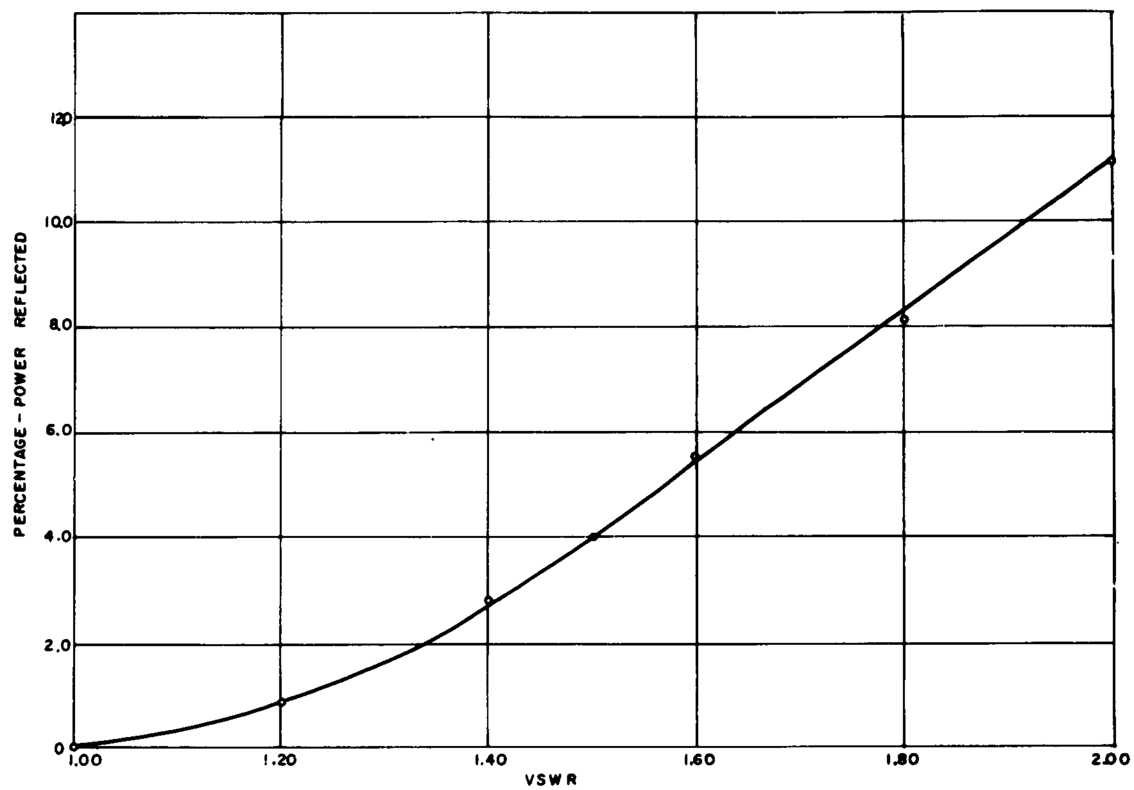


Figure 11. VSWR Versus Power Reflected.

Plots of VSWR versus frequency for the 4-mm and 2-mm calorimeters are given in Figures 12 and 13 respectively.

These microwave coupling factors must be accounted for in an accurate measurement of absolute power, and thus the true power P is given in terms of indicated power P_i as

$$P = \frac{P_i}{\text{RF Efficiency}}$$

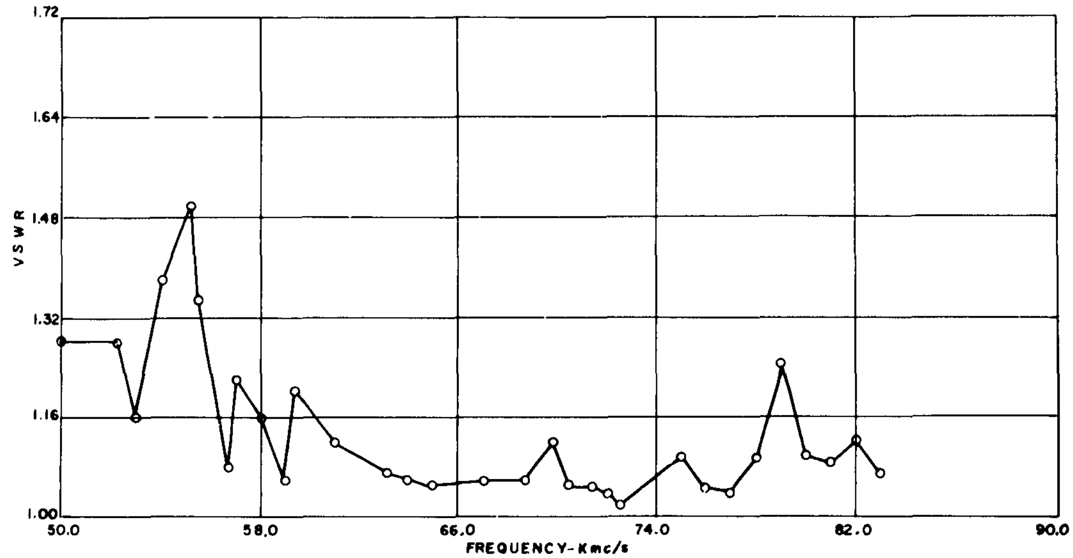


Figure 12. VSWR Versus Frequency, 4-MM Calorimeter. (Frequency: 50-75 kmc/s)

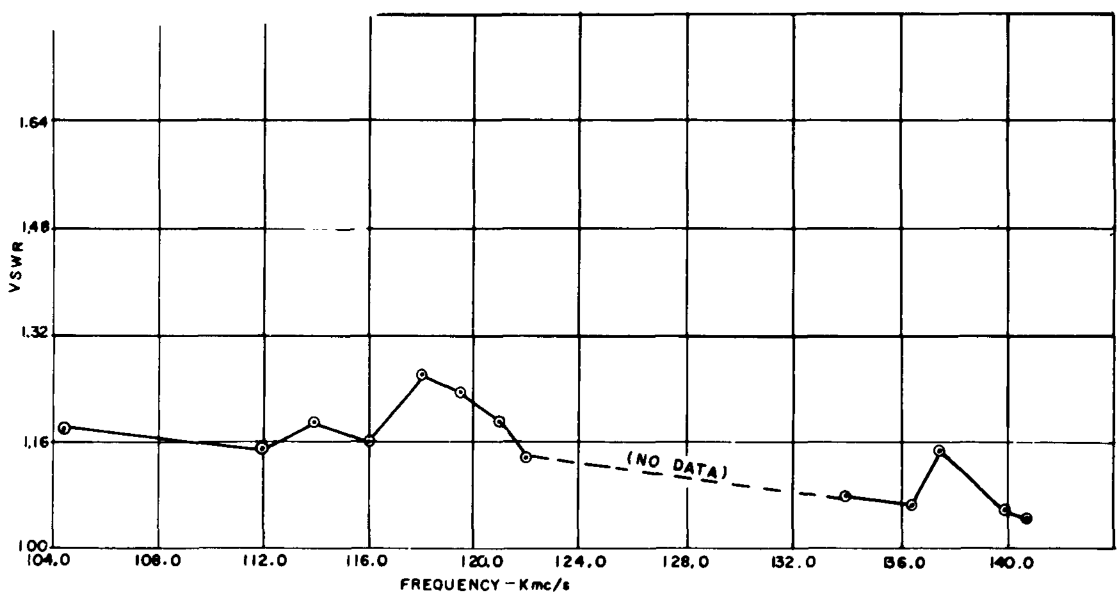


Figure 13. VSWR Versus Frequency, 2-MM Calorimeter. (Frequency: 90-140 kmc/s)

OUTPUT INDICATOR

The thermopile[7] is essentially a voltage output device. Therefore, the measuring instrument must be capable of measuring microvolts of output (negligible current) consistent with a high input impedance meter.

A Leeds and Northrup Model 9385A stabilized d-c microvolter was used for measuring the calorimeter output voltage. The input impedance of this instrument is approximately 12 megohms resistance shunted by 220 microfarads of capacitance.

The drift of this instrument is 0.2 microvolts or less after a warmup time of one minute. Due to the nature of a thermopile circuit producing the emf, residual voltages produced as a result of thermal agitation, and finite variation in velocity may cause stray potentials of either a positive or negative polarity. To correct for these stray potentials of (I) polarity, a drift compensating network was designed to be used externally to the calorimeter and microvolter. This compensator applies a d-c bias, positive or negative, across a resistance which is in series with the thermopile output voltage, (Figure 14). This compensator can zero out any residuals up to a maximum of ±300 microvolts.

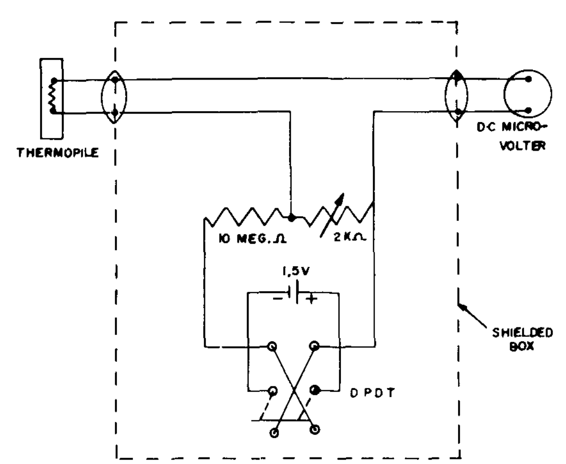


Figure 14. Drift Compensating Network.

CLOSED FLOW RATE SYSTEM

In order to obtain a constant flow of the calorimetric fluid, at a particular flow rate setting, a closed system was used. The flow rate required for measuring milliwatts to several watts of power should be variable for optimum performance of the system.

A heat exchanger was incorporated into this system with a capacity of about 600 cc/minute. As this flow rate was too fast for the particular application, a set of regulator valves was placed in the output line, the bypass line, and the secondary line going to the calorimeter. Very small flow rates may be obtained by this arrangement. Figure 15 depicts the flow rate system and calorimeter.

A precision flowmeter was used to measure the liquid flow rate over the desired range. The particular flowmeter model (Fisher Scientific Cat. No. 11-164) has several precision bore tubes and floats. The capacity of this meter is from .025 to 2100 cc/minute when using the proper tube and float. The range of interest for this particular application is between 5 and 30 cc/minute. Figure 16 is the calibration curve used for setting the flow rate of the system.

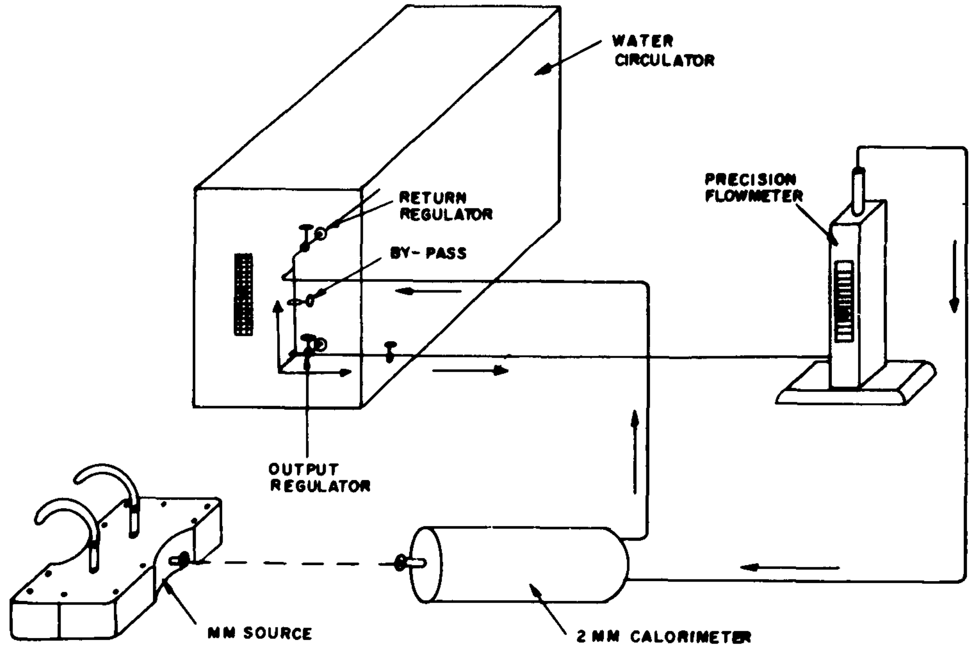


Figure 15. Circulating Flow Rate System.

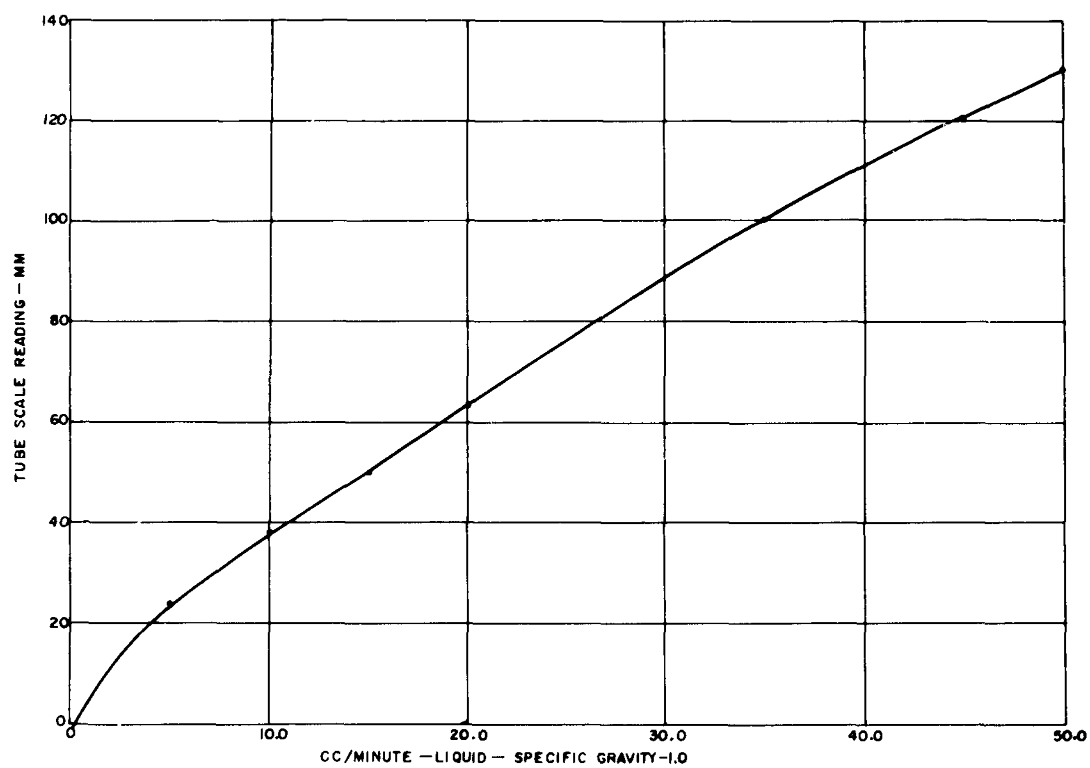


Figure 16. Flowmeter Calibration Curve.
(Tube 06-150)

CONCLUSIONS

The techniques utilized in the design of flow calorimeters are not new and have been used previously in the construction of microwave calorimeters. The 2-and 4-mm calorimeters described in this report demonstrate the advantages of the flow-type calorimeters in directly measuring power over a range of one milliwatt to two watts without the use of auxiliary components. At the time of development, these units were superior in dynamic range of power measurement to comparable commercially available units. They were used to evaluate several COE-40 (4-mm) and two COE-20 (2-mm) carcinotrons. Power outputs in excess of one watt were measured indicating satisfactory performance at these power levels.

The efficiency of the calorimeters is somewhat less than ideal. Both d-c and r-f efficiencies could be increased by fabricating the waveguide loads of plastic, coated with a conductive metal (gold or silver). The metallic walls should be several skin depths in thickness for the frequency range of interest. This technique would eliminate some of the heat lost to the surrounding brass waveguide walls, and thus increase the overall efficiency of the voltage output versus input power.

Since a 1-mm carcinotron, Model COE-10, with a power output of one watt is being developed for Rome Air Development Center, it is of interest to consider, briefly, some of the design problems at this wavelength. At the shorter millimeter wavelengths, the size of components become vanishingly small. For example, the size of the rectangular waveguide for the dominant mode propagation at 1-mm is .034" × .017". At these frequencies, tolerances become extremely small; hence, satisfactory design of a water load is difficult and the attenuation of the waveguide becomes excessive. In order to extend the power measurement capabilities to 1-mm, tapers having a satisfactory impedance transformation may be utilized. Tests performed with the 4-mm calorimeter, using a precision taper to measure 2-mm power, indicate efficiencies between 80 to 90 percent, when compared with the 2-mm unit. Efficiencies obtained with the above technique appear promising for 1-mm power measurements.

APPENDIX I

THERMOPILE OUTPUT VOLTAGE VERSUS FLOW RATE

THERMOPILE OUTPUT VOLTAGE VERSUS FLOW RATE

Output voltage of 100-junction copper-constantan thermopile for flow rates from 1 to 20 cc/minute, range of temperature between 20° - 30° C.

Thermopile output voltage E_0 = 2 microvolts/1 × 10^{-3}° C. Power Sensitivity - P = 70 microwatts/1 × 10^{-3}° C. Less than .3% error.

Flow Rate cm^3/minute	Microwatts/ 1 × 10^{-3} °C. change	Microvolts/ Milliwatt
1.0	70.0	28.60
1.2	84.0	23.80
1.4	98.0	20.40
1.6	112.0	17.86
1.8	126.0	15.88
2.0	140.0	14.28
2.2	154.0	13.00
2.4	168.0	11.91
2.6	182.0	10.99
2.8	196.0	10.20
3.0	210.0	9.52
3.2	224.0	8.93
3.4	238.0	8.40
3.6	252.0	7.96
3.8	266.0	7.52
4.0	280.0	7.14
4.2	294.0	6.80
4.4	308.0	6.50
4.6	322.0	6.21
4.8	336.0	5.95
5.0	350.0	5.72
5.2	364.0	5.49
5.4	378.0	5.29
5.6	392.0	5.10
5.8	406.0	4.92
6.0	420.0	4.76
6.2	434.0	4.61
6.4	448.0	4.46
6.6	462.0	4.33
6.8	476.0	4.20
7.0	490.0	4.08
7.2	504.0	3.97
7.4	518.0	3.86
7.6	532.0	3.76
7.8	546.0	3.66
8.0	560.0	3.57
8.2	574.0	3.48
8.4	588.0	3.40
8.6	602.0	3.32
8.8	616.0	3.25

Flow Rate cm^3/minute	Microwatts/ 1×10^{-3} °C. change	Microvolts/ Milliwatt
9.0	630.0	3.18
9.2	644.0	3.10
9.4	658.0	3.04
9.6	672.0	2.98
9.8	686.0	2.92
10.0	700.0	2.86
10.2	714.0	2.80
10.4	728.0	2.75
10.6	742.0	2.69
10.8	756.0	2.65
11.0	770.0	2.60
11.2	784.0	2.55
11.4	798.0	2.51
11.6	812.0	2.46
11.8	826.0	2.42
12.0	840.0	2.38
12.2	854.0	2.35
12.4	868.0	2.30
12.6	882.0	2.26
12.8	896.0	2.23
13.0	910.0	2.19
13.2	924.0	2.16
13.4	938.0	2.13
13.6	952.0	2.10
13.8	966.0	2.07
14.0	980.0	2.04
14.2	994.0	2.01
14.4	1008.0	1.98
14.6	1022.0	1.95
14.8	1036.0	1.93
15.0	1050.0	1.90
15.2	1064.0	1.88
15.4	1078.0	1.85
15.6	1092.0	1.83
15.8	1106.0	1.81
16.0	1120.0	1.78
16.2	1134.0	1.76
16.4	1148.0	1.74
16.6	1162.0	1.72
16.8	1176.0	1.70
17.0	1190.0	1.68
17.2	1204.0	1.66
17.4	1218.0	1.64
17.6	1232.0	1.62
17.8	1246.0	1.60
18.0	1260.0	1.58
18.2	1274.0	1.57

Flow Rate cm^3/minute	Microwatts / 1×10^{-3} °C. change	Microvolts/ Milliwatt
18.4	1288.0	1.55
18.6	1302.0	1.53
18.8	1316.0	1.52
19.0	1330.0	1.50
19.2	1344.0	1.49
19.4	1358.0	1.47
19.6	1372.0	1.46
19.8	1386.0	1.44
20.0	1400.0	1.43

APPENDIX II

DETAILS OF 2-MM AND 4-MM WAVEGUIDE LOADS

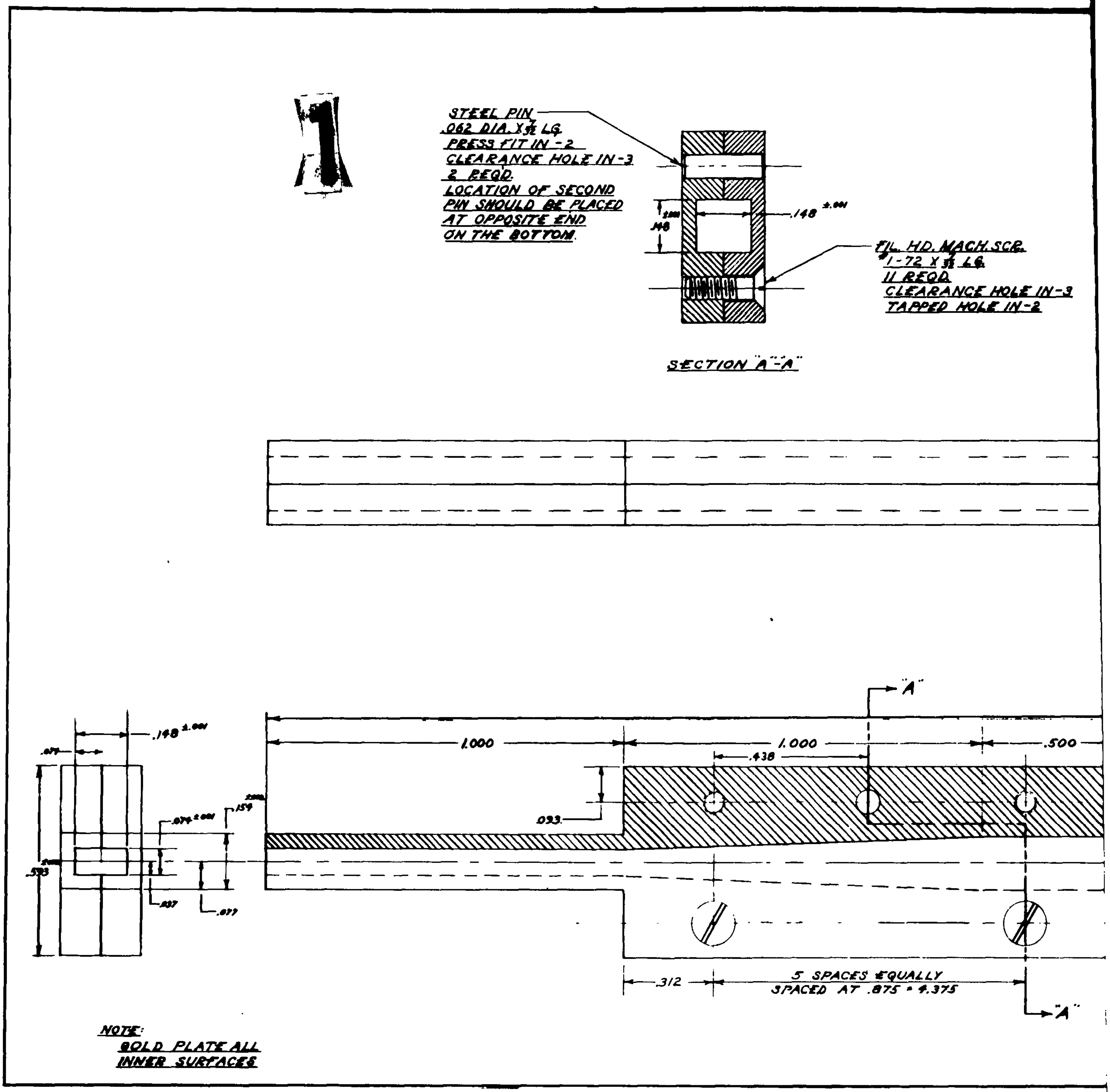
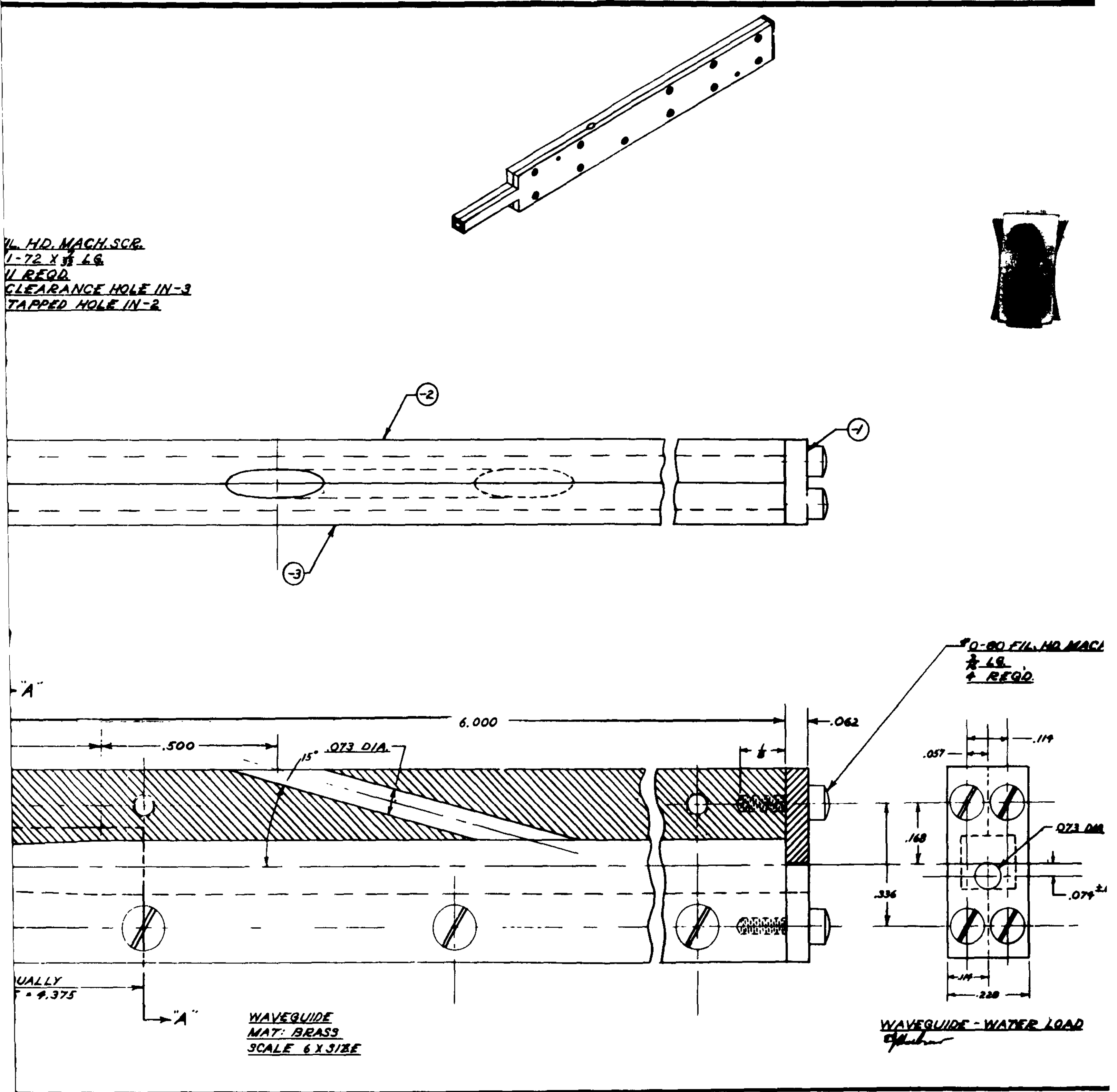


Figure 17. Detail Drawing, 4-MM Wav



Detail Drawing, 4-MM Waveguide Load.

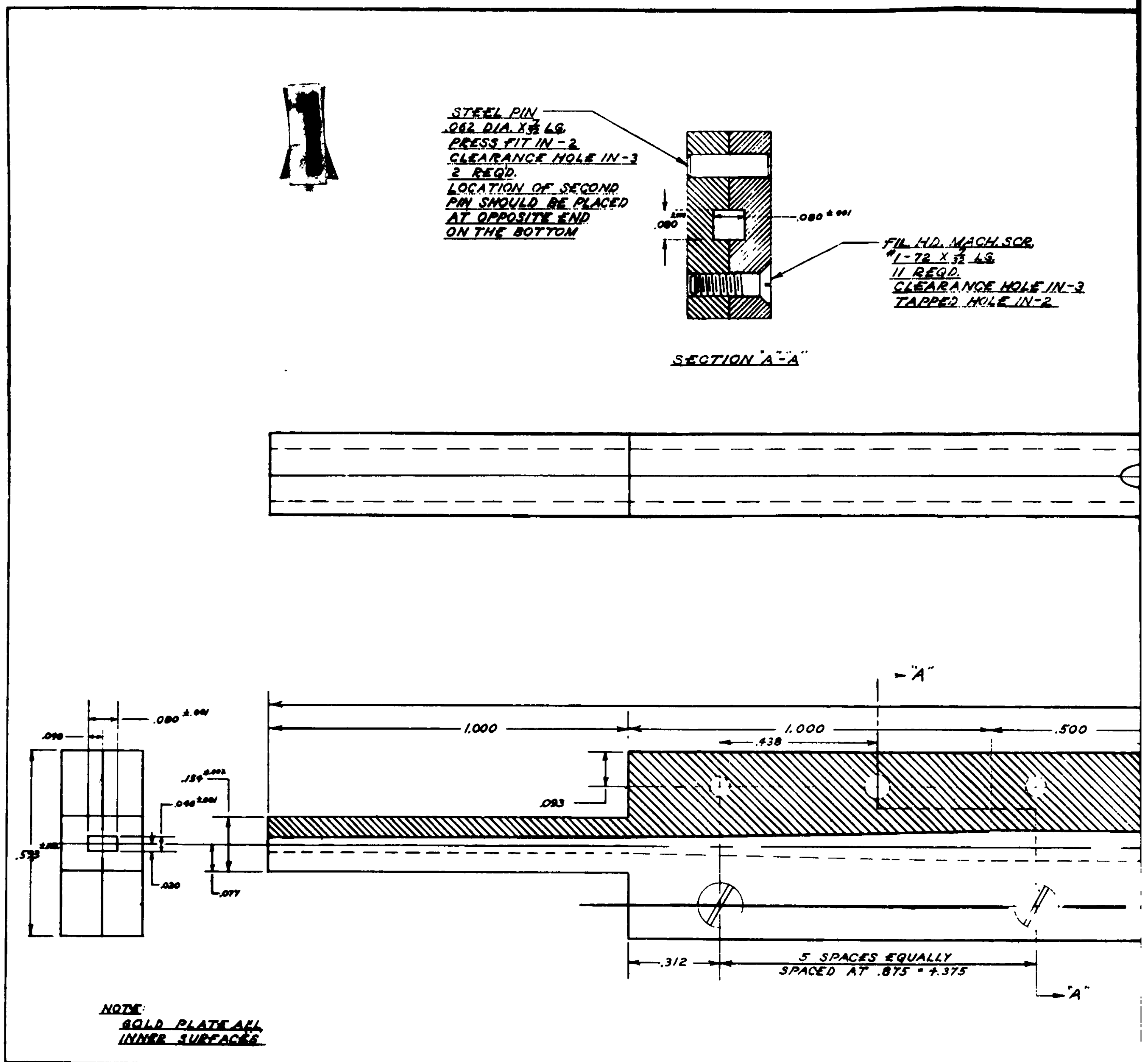
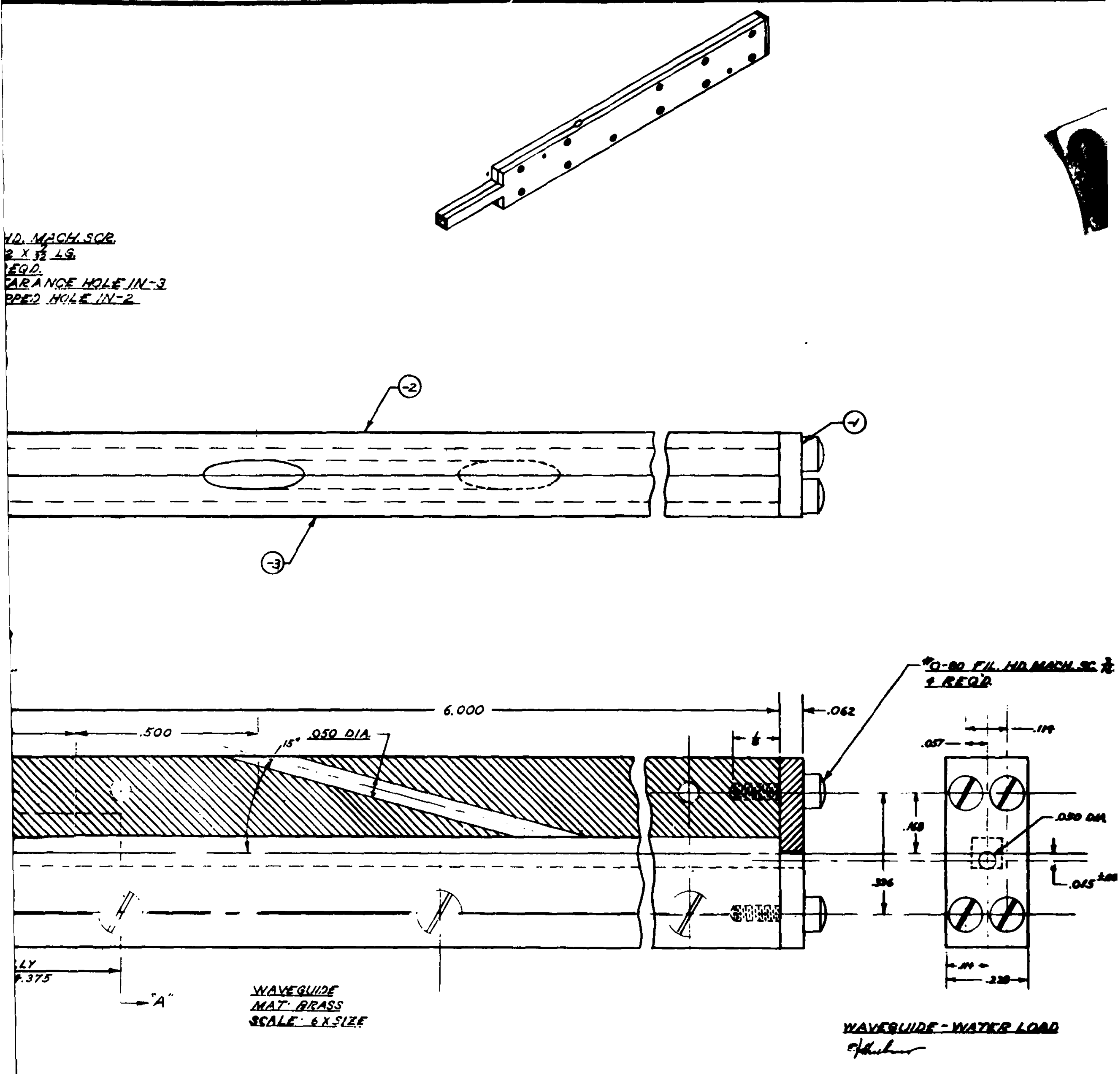


Figure 18. Detail Drawing, 2-MM Waveguid



Drawing, 2-MM Waveguide Load.

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CATALOGUE FILE CARD

Rome Air Development Center, Griffiss AF Base, N.Y.
Rpt No. RADC-TDR-62-600. FLOW CALORIMETERS FOR THE 4-MM AND 2-MM WAVELENGTH RANGE. Dec 62, 27p. incl illus.

Unclassified Report

Present commercial calorimeters operating at wavelengths below four millimeters are limited to the measurement of a maximum of one-half watt of average power, thus requiring the use of precision calibrated attenuators for higher powers. This report describes the mechanical and electrical characteristics of a 4-millimeter (50 to 75 kmc/s) and a 2-millimeter (90 to 140 kmc/s) flow calorimeter capable of measuring several watts of average power. These calorimeters have an advantage over commercially available units by being capable of direct power measurements from one milliwatt to several watts without the use of auxiliary components.

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2. Microwave Equipment
3. Heat

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